Hazard identification and scenario selection of ship grounding accidents

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ABSTRACT

The objectives of the present paper are to identify the hazard of ship grounding; where a ship runs on a rock with a forward speed, and to select a set of credible scenarios with a limited number that can still represent all possible situations of the accidents. For this purpose, the statistics of ship grounding accidents recorded by authorities for the period of 46 years during 1970–2016 are collated. An extensive analysis is undertaken to examine the statistical characteristics in association with random variables influencing the consequence of grounding. A total of six parameters, namely ship's forward speed, ship's trim angle, rock tip eccentricity, rock length, rock width and rock height are considered as random variables where the displacement or mass of the grounded ship is fixed. Each of the random variables is then formulated with a probability density function. A sampling technique is applied to the probabilistic selection of the grounding scenarios which are to be used for the consequence analysis within the framework of quantitative risk assessment. Important insights developed from the present study are discussed. Details of the analyses are documented.

1. Introduction

While in service, ships rarely are subjected to accidents which include grounding, collision, contact, fire, explosion, capsizing and hull girder collapse. Such accidents may result in catastrophic consequences associated with casualties, property damage and environmental pollution. Ship grounding studied in the present paper is one of the most frequent accidents in shipping. When large tankers are involved in a grounding event with breaching one or more cargo tanks, the environmental pollution due to an oil spill becomes a great concern. Fig. 1 shows the causes of oil spills with greater than 700 tonnes in amount occurred during 1970–2015 (ITOPF, 2016). It is seen from Fig. 1 that grounding accidents take up 33%. AGCS (2014) indicates that ship grounding takes up 50% of all marine insurance claims in excess of 1 m Euro during 2009–2013. Moreover, wreck removal costs can be several times larger than that of the hull value in some cases, because rescue and salvage operations are complex and costly as environmental concerns are raised. For example, the passenger vessel "*Costa Concordia*", which ran aground in 2012, significantly raised many issues to be resolved in the international marine salvage industry and caused new regulations to be set for improving safety performance in wreck removal operations (Senauth, 2013).

The International Maritime Organization (IMO, 2002) introduced a procedure for formal safety assessment (FSA) which is handy in identifying and evaluating risks to personnel, assets and the environment. The FSA procedure comprises five main steps as follows:

- Step 1: Hazard identification.
- Step 2: Risk analysis
- Step 3: Risk control options
- Step 4: Cost-benefit assessment
- Step 5: Decision making and recommendations

In step 1, all potential hazards leading to damages to personnel, asset and the environment are identified. The main result of this step is a list of hazards and associated scenarios which should be prioritized by identified risk level that should be the focus of a more thorough analysis in subsequent phases of the FSA. The accidental scenario identification and selection is the most vital stage of any risk assessment procedure or quantitative risk assessment and management (QRA&M), which affects all the following stages in the FSA framework.

Two available approaches can be used for the scenario identification stage; deterministic and probabilistic. In the deterministic procedure, a few scenarios are chosen by assuming a certain value for each scenario

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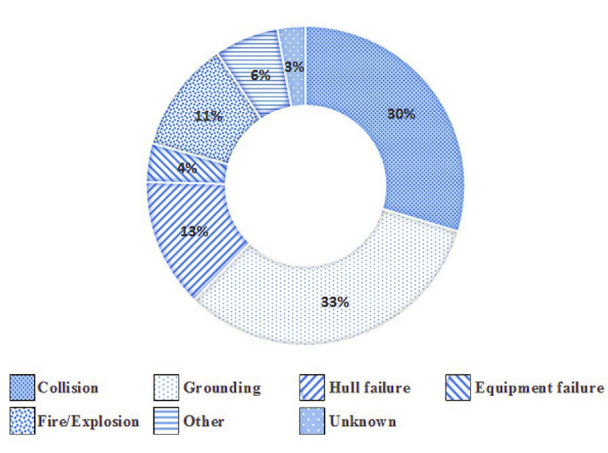 *E-mail address:* samyoussef@aast.edu (S.A.M. Youssef).

Fig. 1. Causes of oil spills with greater than 700 tonnes in amount for the period 1970–2015 (ITOPF, 2016).

parameter where the ship might be tested under one or more unfavorable accidental scenarios with a relatively low level of occurrence probability, leading to unfavorable consequences. On the other hand, the probabilistic approach identifies the hazards probabilistically with a set of scenarios in association with the random variables affecting the consequences of the accident (Paik and Thayamballi, 2007; Samuelides

et al., 2009; Youssef et al., 2016). As ship grounding is rather uncertain and probabilistic in nature, probabilistic approaches are more desirable.

Numerous studies in the literature have used the deterministic approach to choose grounding scenarios, which were implemented in model tests and numerical simulations (Glykas and Das, 2001; Haris and Amdahl, 2012; Hong and Amdahl, 2008, 2012; Liu et al., 2015; Paik and Seo, 2007; Yu et al., 2013; Zeng et al., 2016; Zhang and Suzuki, 2006). In contrast, a few studies have used the probabilistic approach, in which each of grounding parameters has been dealt as a random variable by formulating a distribution function. Based on statistical data collected, Brown and Amrozowicz (1996) introduced a method to define probability density distributions for grounding damage extent as a function of a simplified set of independent variables circumscribing the ship structural design. This method is initially started by formulating probability density functions (pdf's) for ship speed, depth of water and obstruction characteristics. Similar work was conducted by Lützen and Simonsen (2003) where the grounding scenarios were described by pdfs for ship draught, speed and obstruction height, and width. Moreover, such analyses have also been performed by Rawson et al. (1998) and Tikka and Chen (2001). In recent years, the studies on the structural crashworthiness and also the response of post-grounding accidents are also found in the literature (Deeb et al., 2017; Hong and Amdahl, 2008; Khan and Das, 2008; Paik, 2007a, b; Samuelides, 2015; Zipfel and Lehmann, 2012).

In the light of the above discussion, this paper aims the way to select grounding scenarios using the probabilistic approaches. This method commences with collecting grounding accident database from different
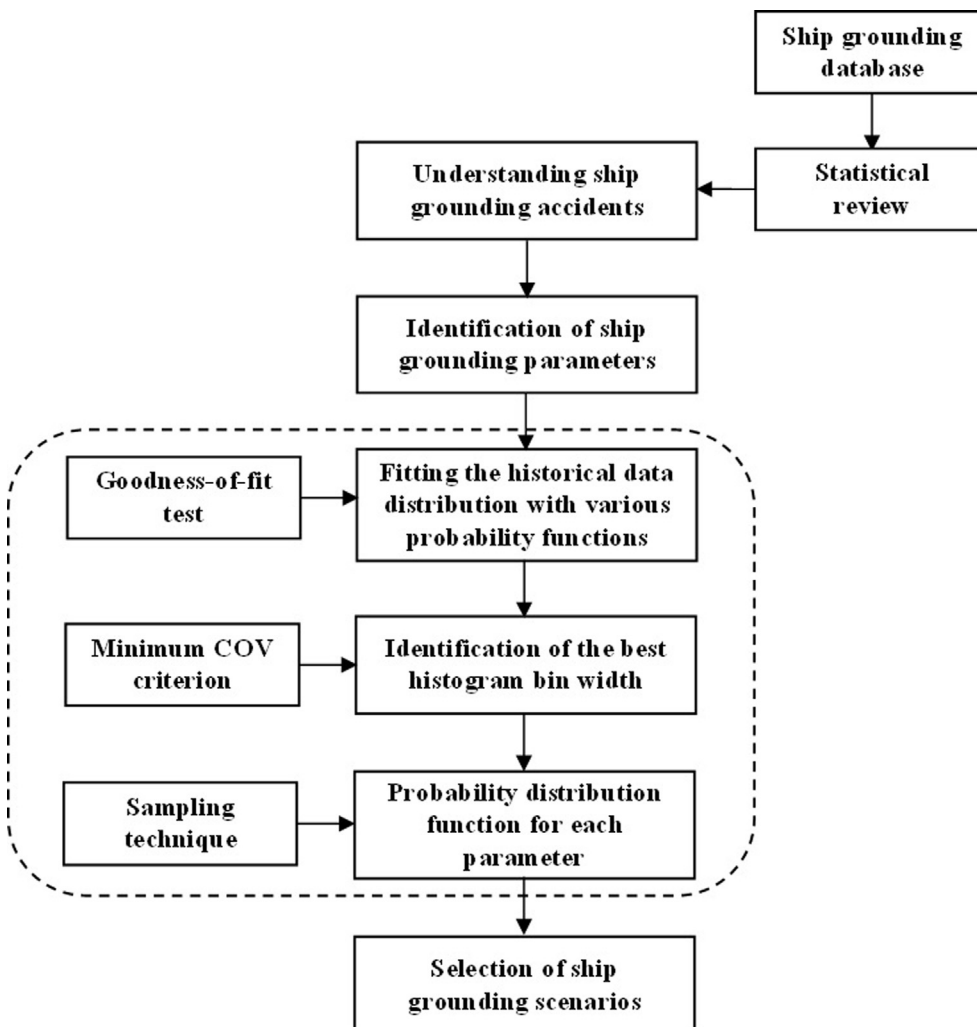

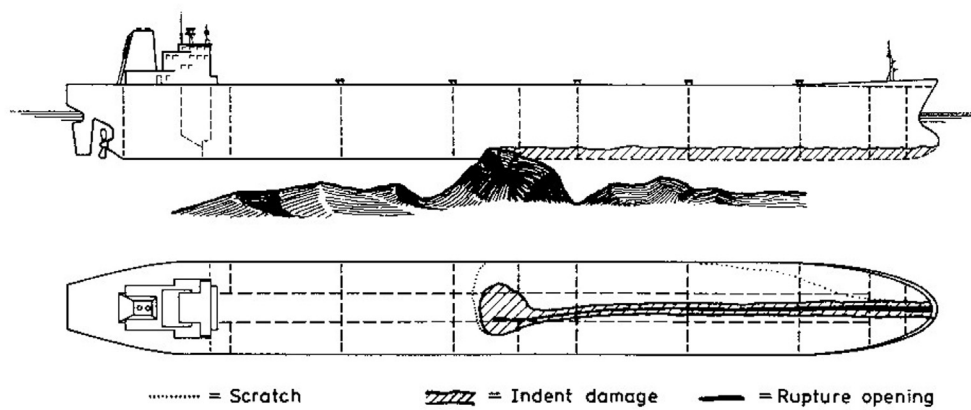**Fig. 2.** Framework of selecting the grounding scenarios.

Fig. 3. A schematic of the grounding accident and the resulting bottom raking damage distribution (Kuroiwa, 1996; Pedersen and Zhang, 2000a).

Table 1
Quantity of grounding parameters recorded in the database.

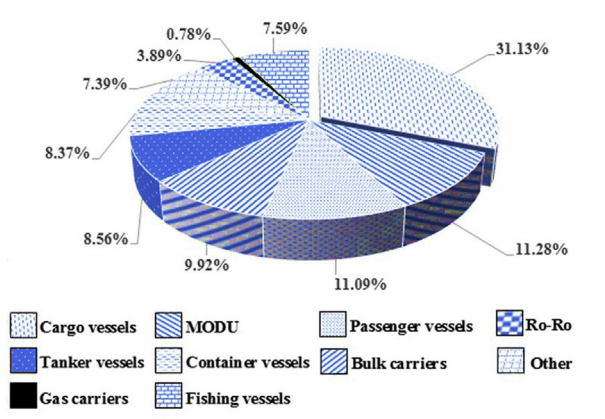| Parameters	Quantity
Complete principal dimension	458
Deadweight (DWT)	405
Gross tonnage (GRT)	481
Age	458
Impact speed (v_i)	320
Forward and aft drafts	198

Fig. 4. Distribution of ship types in groundings.

sources worldwide, followed by a statistical analysis which aids formulating the pdf's for the corresponding parameter of grounding. The derived probability functions are then used to select a set of grounding scenarios that can typify all possible situations. Similar approaches were applied to ship collisions (Youssef et al., 2014a, 2014b).

2. Framework of the applied methodology

To choose accidental scenarios, influential parameters governing the accident are defined in Section 3. This can be done by discerning the event first through investigating a large number of historical relevant accidents. The probabilistic method presented in this study starts with gathering information about historical ship grounding accidents to erect a database with a satisfying quality and quantity. The outline of the framework developed in this study is illustrated in Fig. 2. The established database will be then employed to perform an extensive statistical analysis. The database and the obtained statistical analysis will carefully be investigated to identify the most effective parameters that control the

grounding event. This can also be used to examine the relationships between parameters of influence.

The historical data distribution for each parameter should be fitted well by a probability density function (pdf) with a description of the range and variability of such parameter. Goodness-of-Fit test (GoF) can be implemented to measure the compatibility of historical data with the candidate pdf's. Due to the significant effect of the histogram bin width (or interval) on the data distribution properties such as the mean, the variance and the coefficient of variance (COV), Paik and Kim (2012) put forward the so-called 'Minimum COV criterion' which guarantees that the degree of variation between the candidate pdf's and the original data distribution will be the lowest. Thus, the bin width that accompanies the largest mean value and the smallest COV shall be selected. By applying the above steps, which are grouped in a dashed box shown in Fig. 2, one pdf should be nominated for each grounding parameter identified in advance. Finally, the determined pdf's will be employed as inputs to one of the most confident sampling techniques to contrive a limited number of grounding scenarios, since considering all possible scenarios is not practical. Latin hypercube sampling (LHS) (Ye, 1998) and Monte Carlo simulations (MCS) (Rubinstein, 1982) are the most commonly used sampling techniques. The resulted scenarios can be employed to simulate structural crashworthiness of the grounded ship.

3. Parameters affecting ship grounding mechanics

Ship grounding is defined as an accidental event where ship bottom structures are damaged. Typically, ship grounding accidents can be classified into two groups: one is an event where a ship runs on a rock pinnacle with a forward speed, and another group is a stranding situation which is similar to a collision where the bottom structures are subjected to mainly out-of-plane loads (Paik and Thayamballi, 2003). In the first group, the grounding process is distinguished by an obstruction deflects the bottom inward and/or enters into and cuts through the bottom structures as the ship travels forward.

This paper focuses on the former group of grounding, which is usually the consequence of navigational errors associated with failures in the process of passage planning and piloting as well as nautical charts with un-updated data (Fowler and Sørgård, 2000). The grounding damages in this case are governed by the loading in the ship's length direction causing a raking situation as shown in Fig. 3. The amount of grounding damages is contingent on the resistance of bottom structures to the penetration as well as operational conditions such as grounding speed, hydrodynamic stability and rock characteristics. This kind of a raking accident often causes a very long gash in the bottom structures. On the other hand, the stranding situation happens when a ship is swept away by waves and tides as the engine power fails, where bottom structures on a rock near shore are damaged by vertical loading due to the difference between buoyancy and weight in ebb tide.
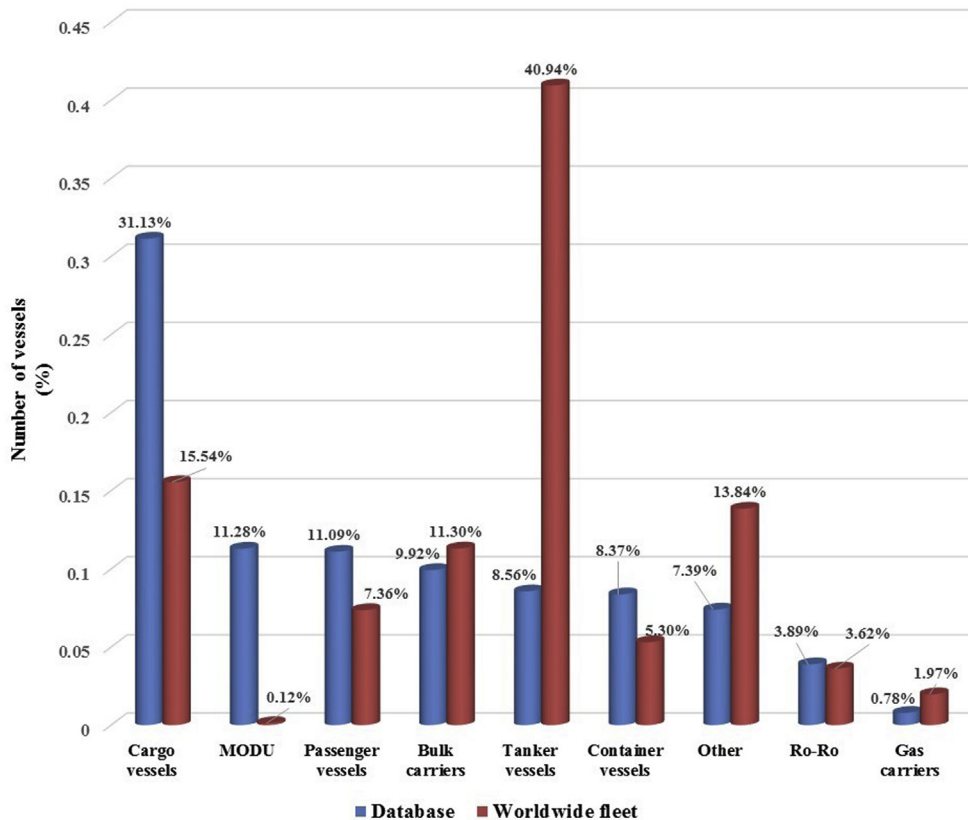
Fig. 5. Distribution of ship types in grounding accidents versus the worldwide fleet.
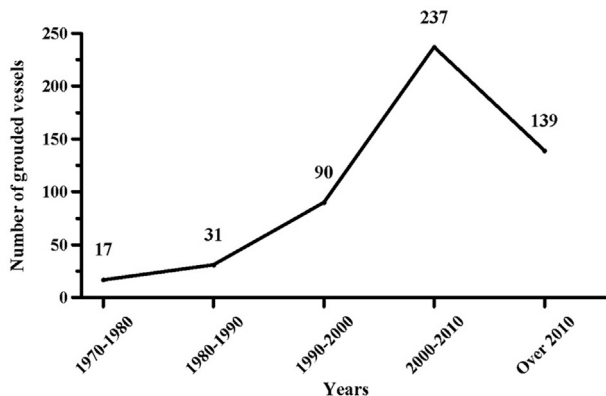

Fig. 6. Number of grounded vessels by one-decade interval.

Based on the seabed topology, the grounding can be classified into hard and soft grounding. When the ship runs aground on rocks or hits a rocky side of the coasts by wind or waves, the event can be referred to as 'hard grounding' causing extensive crushing and tearing damage. Contrastingly, the soft grounding refers to the event where a ship runs aground on soft seabed like sandy beaches causing minor damage on a large area in some cases (Kaneko, 2012; Lützen and Simonsen, 2003; Mazaheri, 2009).

Tasks for analyzing ship grounding accidents can be bisected into the following: namely the external mechanics and the internal mechanics (Paik and Thayamballi, 2003). The aim of the external mechanics is to identify the accidental actions or loads, by taking into account the effects of accidental and operational conditions of the grounded ship. The aim of the internal mechanics is to identify the structural consequences of the grounded ship.

Similar to other types of accidents in association with volatility, uncertainty, complexity and ambiguity (VUCA), ship grounding mechanics is also governed by various parameters which are random. Within the framework of quantitative grounding risk assessment and management, it is required to select accidental scenarios associated with the VUCA aspects, which are necessitated to characterize the accidental actions and action effects.

Parameters affecting ship grounding mechanics with the focus on the grounding on a rock with a forward speed can be inventoried as follows:

- mass of the grounded ship,
- ship's forward speed,
- ship's trim angle,
- eccentricity of rock tip,
- length of rock,
- width of rock, and
- height of rock.

In the present study, the parameters noted above are tackled as random variables, except the mass of the grounded ship because the quantitative grounding risk assessment will be executed for a certain ship in question. Probability density distributions of the parameters are distinguished based on the statistical database of ship grounding accidents. A set of credible grounding scenarios is then selected in a probabilistic way.

4. Collation of ship grounding accident database

Two kinds of casualty databases are available: accessible by the public and privately owned databases (i.e., commercial data). One of the publicly accessible data is the national accident investigation boards (flag administrations). In this study, a ship grounding database has been amassed from more than 600 accidents investigation reports located in the web pages of about 19 national accident investigation boards,
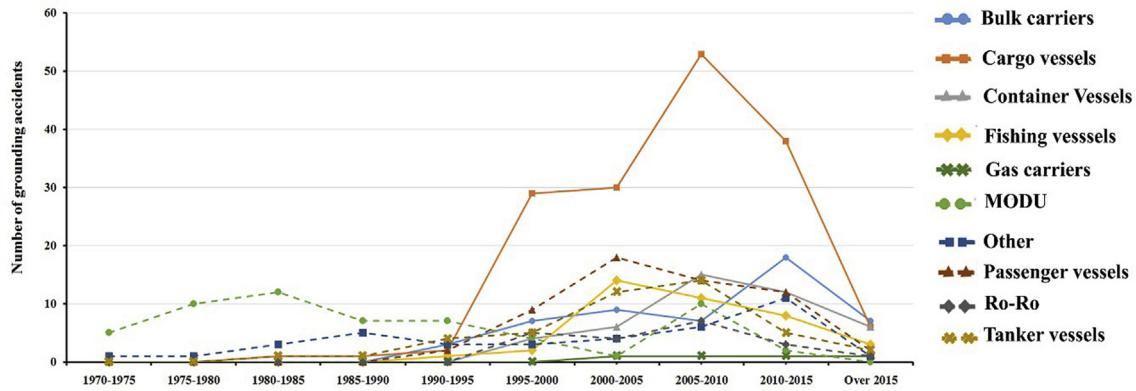
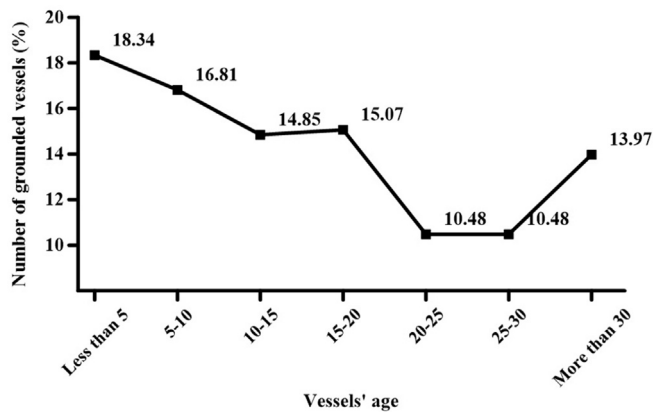**Fig. 7.** Grounding accidents versus vessel types per five-year interval.

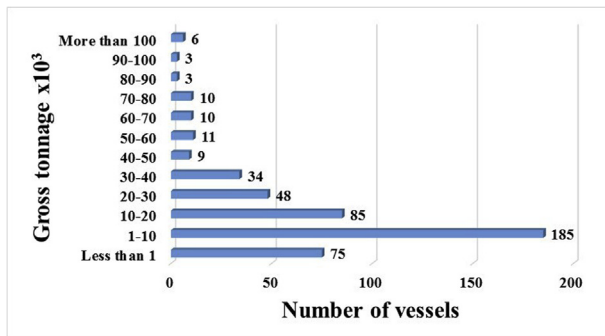**Fig. 8.** Number of grounded vessels versus ship age.

Fig. 10. Number of groundings versus non-dimensional impact speed.

Fig. 9. Number of groundings by vessel size in gross tonnage.
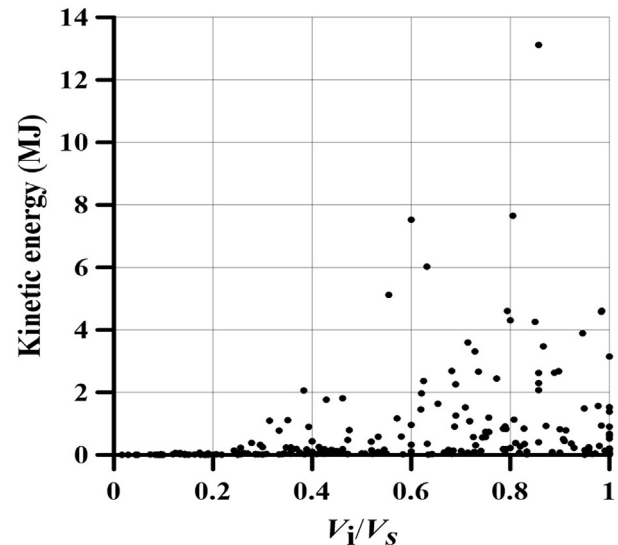
Fig. 11. Grounding kinetic energy versus non-dimensional impact speed.

transport safety bureaus of different countries and non-governmental associations for the period of 1970–2016 (AIBN, 2017; ATSB, 2017; BEAmer, 2017; BMA, 2017; BSU, 2017; DMIB, 2017; EMSA, 2017; HBMCI, 2017; JTSB, 2017; MAIB, 2017; MARDEP, 2017; MaritimeNZ, 2017; MARS, 2017; MCIB, 2017; MSA, 2017; NTSB, 2017; SHK, 2017; SIA, 2017; TSB, 2017). All of these boards are interested in covering all accidents in national waters, and all accidents involving their nationally flagged vessels worldwide. The acquired casualty data has been filtered by omitting insufficient and unconscionable data as well as deleting the doubles.

After the database filtration process, the total number of ship grounding accidents became 514 incidents. Unfortunately, not all of publicly accessible accidental reports provide full information about the accident, especially the impact speed, forward and aft draughts at time of

accident. Moreover, it's rare to find reports describing the resulted damage in terms of size and location. Table 1 summarizes the quantity of the most governing parameters recorded in the grounding database.

4.1. Qualitative investigation of grounding statistics

Creating accidental scenarios based on historical data needs accurate and comprehensive statistical reviewing. In that aspect, the collected database is used to show some interesting statistics concerning the ship
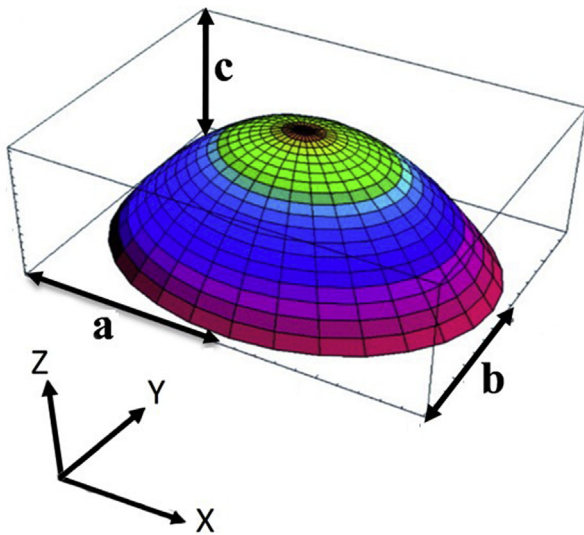
Fig. 12. Geometric model of the seabed obstruction shape.

groundings according to the purpose of the study. This is performed by analyzing the number of grounding accidents distribution related to the characteristics of grounded vessels such as; type, size, age, date of accident, speed and the kinetic energy at the time of accident.

The database collected by Simonsen and Hansen (2000) with 200 grounding accidents during the period of 1945–1960 may also be referred to. In the European Union research project titled "HARDER", damage database has been collected including 930 grounding accidents for the period of 1944–2000. HARDER (1999–2003) has introduced probability density distributions for the damage extents: damage height, width, length, and position. Recently, a similar project called "Goal-Based Damage Stability" (GOALDS) has been launched aiming to improve the current survivability methods of vessels subjected to collision and grounding damage (GOALDS, 2009–2012). In this project, the database developed in the HARDER project has been redefined and enhanced by collecting additional collision and grounding accident data to cover the period of 2000–2009 from additional sources. More details about the GOALDS's updated damage statistics can be found in IMO (2012).

In order to relate the grounding accidents to the ship type, all ships in database have been classified into 10 major categories as follow;

- Tankers: including crude, product and chemical tankers and other liquid carriers.
- Bulk carriers: including dry bulkers and coal carriers.
- Cargo vessels: including general cargo and refrigerated vessels.
- Container vessels.
- Gas carriers: including liquefied natural gas (LNG) and liquefied petroleum gas (LPG) carriers.
- Roll-on/roll-off (Ro-Ro) vessels: including car carriers, Ro-Ro/cargo, and Ro-Ro container vessels.
- Passengers: including passenger vessels and ferries.

- Mobile offshore drilling units (MODU): including jack-ups, semi-submersibles, and drill ships.
- Fishing vessels: including all types of fishing vessels.
- Other: including, factory vessels, heavy lift vessels, tug boats, pleasure boats and yachts.

Fig. 4 shows the distribution of ship types involved in grounding accidents. It is seen that cargo vessels are the most frequently involved in grounding with 31% of total accidents in the database. This is due to the fact that the shipping routes of the general cargo ships is usually the busiest, and most of them operate in short sea routes or in trafficked coastal areas with enough risk of being damaged by submerged reefs and rocks (Bužančić Primorac and Parunov, 2016).

The ship type's distribution is calculated by inspecting worldwide fleets recorded in the Shipping Intelligence Network of Clarkson's database (Clarkson, 2017). The obtained distribution is then compared with the distributions of ship types in grounding accidents within the database as shown in Fig. 5. It is noted that the cargo vessels are overrepresented within the grounding accidents database (IMO, 2012).

Figs. 6 and 7 present the number of grounded vessels by one-decade interval and five-years interval, respectively. The figures show that the number of groundings escalates until 2010 with the peak the period of 2005–2010. The number of groundings has dwindled down in recent years with a help of advanced technologies for navigations and designs together with enhanced rules.

Figs. 6 and 7 present the number of grounded vessels by a one-decade and a five-years interval, respectively. The figures show that the number of groundings escalates until 2010 with the peak the period of 2005–2010. The same tendency has been observed by Eleftheria et al. (2016) and AGCS (2016) and other studies. This increase in number can attributed to the increased habit of reporting this type of accidents during this period of time (Eleftheria et al., 2016). The number of groundings has witnessed a dwindling down during the following years which happened due to the help of advanced technologies for navigations and designs together with enhanced rules (Bužančić Primorac and Parunov, 2016).

Fig. 8 presents the trend of groundings with vessels' age. It is seen that the youngest vessels (below 5 years) are most frequently involved in groundings with 18% of the accidental database. This may be due to the fact that such young vessels are associated with unprecedented maneuvering incidents, communication problems, crew's inability to handle new technology equipment, their unfamiliarity with the new ship or unexpected failures from the newly installed machinery (Papanikolaou and Eliopoulou, 2008). On the other hand, old vessels (above 25 years) are facing grounding with 24.5% of the accidental database. This may be due to less advanced navigational equipment onboard and ship performance degradation as well as the reliability of the mechanical parts. Moreover, the improper bridge design in older vessels may cause accidents if the steering, radar and charts are located on different positions of the bridge (Mazaheri, 2009).

Focusing on the size of vessels involved in grounding available in the database, the distribution of groundings with respect to ship size in gross tonnage (GT) is explored as shown in Fig. 9. It is observed that the most groundings occur in vessels below 10,000 GT in size (with 54% of the

Table 2
K-S test statistic values for candidate pdfs for the category including all types of ships.

|	Used pdfs						
	Logistic	Lognormal	Normal	2-P Weibull	3-P Weibull	2-P Gamma	3-P Gamma
V_i/V_s	0.12571	0.16722	0.10312	0.15816	0.08902	0.14667	0.11454
θ_t	0.16288	n/a	0.18547	n/a	0.23212	0.23212	0.18482
l/L	0.37022	0.17949	0.36403	0.39633	0.23879	0.33225	0.27628
w/B	0.39123	0.24178	0.38263	0.29567	0.2783	0.32976	0.2783
d/D	0.3834	0.29936	0.37569	0.3428	0.31215	0.28941	0.34448

Note: 2-P = two parameters, 3-P = three parameters.
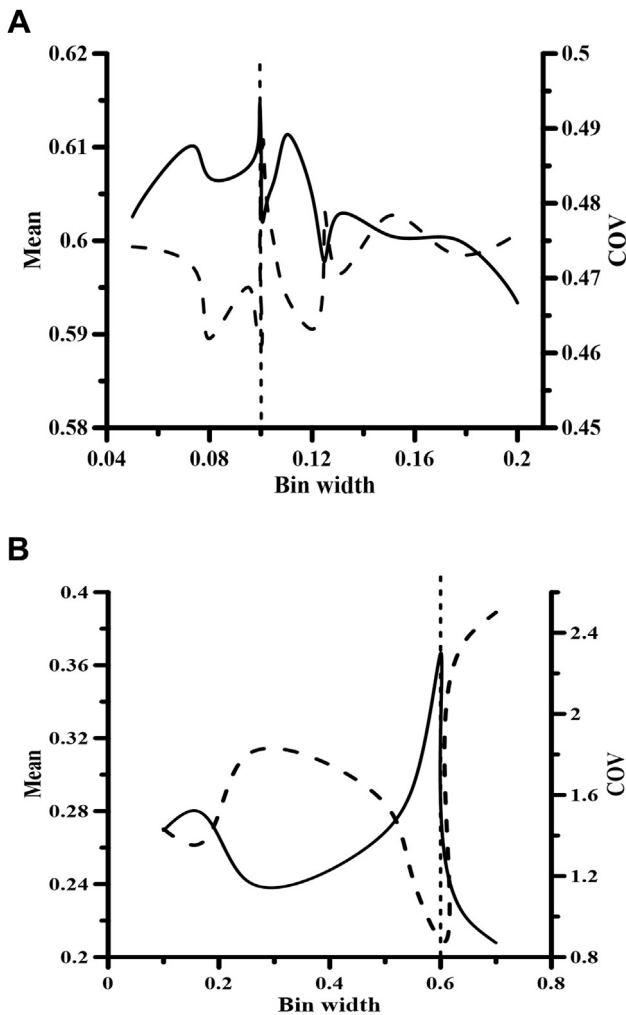
Fig. 13. Best histogram bin width (interval) determination process. (a) Non-dimensional impact speed (V_i/V_s); (b) Trim angle (θ_t).

total number of vessels in the database) compared to the large-sized vessels greater than 20,000 GT in size. This could reflect the vessel operating routes with frequent visits and sailing near to coastal areas. It is expected because the large majority of which are coaster cargo vessels, tug boats, fishing vessels and pleasure boats. A similar observation was made by Samuelides et al. (2009) and the Norwegian Maritime Directorate (NMD, 2011).

The vessel's speed at time of grounding is one of the most dominating parameters which has a great influence in the estimation of the kinetic energy as well as the resulted structural deformation. Comparing the impact speed V_i with the ship's service speed V_s may reflect the navigator's awareness of the accident. In this regard, the impact speed is defined as the relative ship speed, i.e., V_i/V_s for each grounding case found in the database. Fig. 10 shows the distribution of the impact speed in terms of the relative ship speed. It is noticed that the most frequent grounding speed lies between 80 and 100% of the ship's service speed. A similar observation is also addressed by Cerup-Simonsen et al. (2009).

The kinetic energy at the moment of grounding can be calculated once the ship displacement and the speed at time of accident are known. The effect of added mass with 5% of the ship displacement is often considered in industrial practices (Zhu et al., 2002). Fig. 11 presents a scatter plot of the V_i/V_s - the corresponding kinetic energy at the time of accident, where no obvious trend is relevant.

4.2. Modelling of seabed obstruction

The shape and size of the seabed obstruction have an immense effect on the determination of the extent of grounding damage on ships. Alsos and Amdahl (2007) classified the seabed topology into three major types namely rock, shoal and reef. Concerning the resulted bottom damage, rocks cause an extensive plate cutting with deep penetration, while shoals cause a large damage surface with no tearing in some cases. However, there is no adequate information about the seabed topology.

While the seabed is arbitrary in shape, simplified models are available in the literature representing the geometric shape of the seabed: blunted cone-shaped (Naar et al., 2002; Rawson et al., 1998; Simonsen, 1997; Sirkar et al., 1997; Wang et al., 2002), wedge-shaped (Lu and Calladine, 1990; Paik, 1994; Wang et al., 1997), mathematical-modeled rock with polynomial (Heinvee et al., 2013) and paraboloid equations (Nguyen et al., 2011a). The last two types have been used to generate different shapes of the seabed by changing the equation's parameters. Recently, Sormunen et al. (2016) have seen to geological formations of the seabed to develop mathematical rock models for a specific region. Bearing in mind the available historical damage statistics (i.e., extents of damage) from potential sources of sea foor obstruction data, it is possible to establish a simplified indenter by translating such damage data to predict a three-dimensional rock model (Alsos and Amdahl, 2007).

Probabilistic damage models are also available on the basis of large number of collected grounding accidents. IMO (1995) presented a probabilistic procedure for assessing the oil outflow performance of an oil tanker design in collision and grounding based on the damage data of 63 grounding accidents which has been collected during the period of 1980–1990.

In the present study, the seabed topology is associated with the probability density distributions of the damage extents based on GOALDS's updated damage database. By doing this, the longitudinal, transverse, vertical (i.e., penetration) extents of damage can be represented by the length, width, and elevation of the seabed obstruction, respectively (Lützen and Simonsen, 2003). It means that the length and width of the obstruction are measured at the vessel's baseline and the elevation is measured from baseline to the tip of the obstruction (Nguyen et al., 2011b; Pedersen and Zhang, 2000b). A parabolic shape is selected to mathematically represent the seabed obstruction, expressed by Equation (1) that can give an infinite number of shapes. A set of different shapes is generated by heeding the parameters a, b and c as random variables described by pdfs. Fig. 11 shows the geometric model of the obstruction shape with its parameters. As shown in Fig. 12, the length (l), width (w) and the elevation (d) of the proposed obstruction equal to 2a, 2b, and c, respectively.

$$-\frac{x^2}{a^2} + \frac{y^2}{b^2} = \frac{z}{c} \tag{1}$$

In this model, the obstruction tip eccentricity (i.e., the transversal position of the obstruction along the ship breadth) is not yet realized, as no grounding damage database is available. However, to cover all possible scenarios, it is reasonable to suggest that the obstruction tip position at the ship breadth has a uniform distribution (Bulian et al., 2016; IMO, 1995, 2012; Lützen and Simonsen, 2003).

On the basis of the statistical review done for the database and the available seabed obstruction models, the grounding scenarios herein are characterized by the following parameters;

- Non-dimensional impact speed (V_i/V_s): impact speed at time of accident normalised by the ship service speed.
- Ship trim angle (θ_t): positive degrees for trim by aft.
- Obstruction tip eccentricity (e): non-dimensional distance from the ship centerline to port or starboard side.
- Obstruction size (see Fig. 12):
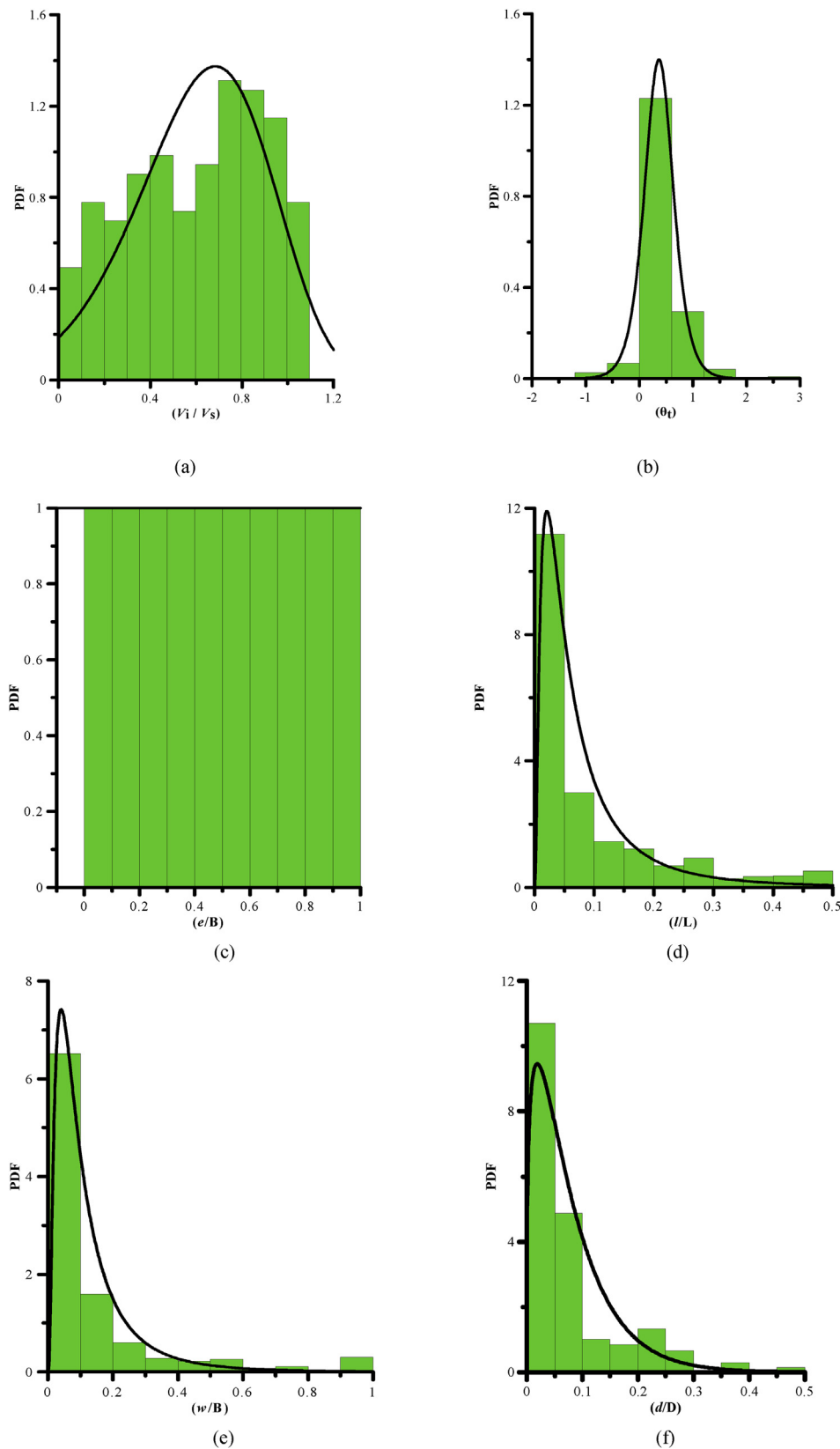
Fig. 14. Selected pdfs for each grounding parameters. (a) Non-dimensional impact speed (V_i/V_s); (b) Trim angle (θ_t); (c) Non-dimensional obstruction tip eccentricity (e/B); (d) Non-dimensional obstruction length (l/L); (e) Non-dimensional obstruction width (w/B); (f) Non-dimensional obstruction elevation (d/D).

o Non-dimensional obstruction length (l) normalised by the ship length between perpendiculars (L) (l/L) (IMO, 2012).

o Non-dimensional obstruction width (w) normalised by the ship moulded breadth (B) (w/B) (IMO, 2012).

o Non-dimensional obstruction elevation (d) normalised by the ship moulded depth (D) (d/D) (IMO, 2012).

In summary, each scenario can be delineated by six parameters which

Table 3
Selected pdf characteristics for all types of ship category.

All types									
V_i/V_s		θ_t		l/L		w/B		d/D	
3-P Weibull		Logistic		Lognormal		Lognormal		2-P Gamma	
w(6.526,1.697,-0.967)		L(0.3666,0.1786)		lnN(-2.896,0.9912)		lnN(-2.41,0.8893)		Γ(1.313,0.06)	
Max	1	Max	2.60256	Max	0.5	Max	1	Max	0.5
Min	0.01622	Min	−1.16914	Min	0	Min	0	Min	0
Interval	0.09955	Interval	0.6	Interval	0.05	Interval	0.1	Interval	0.05

Table 4
Selected pdf characteristics for tankers.

Tankers									
V_i/V_s		θ_t		l/L		w/B		d/D	
2-P Weibull		Logistic		2-P Gamma		Lognormal		2-P Gamma	
W(1.938,0.5998)		L(0.3966,0.1647)		Γ(1.242,0.07337)		lnN(-2.289,0.9598)		Γ(2.995,0.03151)	
Max	1	Max	1.07742	Max	0.5	Max	1	Max	0.5
Min	0.09375	Min	0	Min	0	Min	0	Min	0
Interval	0.3	Interval	0.33	Interval	0.05	Interval	0.1	Interval	0.05

Table 5
Selected pdf characteristics for bulk carriers.

Bulk Carriers									
V_i/V_s		θ_t		l/L		w/B		d/D	
3-P Weibull		Normal		2-P Gamma		Lognormal		2-P Gamma	
W(7.504,1.811,-1.068)		N(0.2533,0.2323)		Γ(1.242,0.07337)		lnN(-2.289,0.9598)		Γ(2.995,0.03151)	
Max	1	Max	1.07742	Max	0.5	Max	1	Max	0.5
Min	0.07333	Min	0	Min	0	Min	0	Min	0
Interval	0.24	Interval	0.17	Interval	0.05	Interval	0.1	Interval	0.05

Table 6
Selected pdf characteristics for cargo vessels.

Cargo Vessels									
V_i/V_s		θ_t		l/L		w/B		d/D	
3-P Weibull		Logistic		2-P Weibull		2-P Gamma		Lognormal	
w(2511,563,-562.2)		L(0.3469,0.1867)		W(0.8836,0.8363)		Γ(1.568,0.06549)		lnN(-2.548,0.7144)	
Max	1	Max	1.47730	Max	0.5	Max	1	Max	0.5
Min	0.02857	Min	−1.16914	Min	0	Min	0	Min	0
Interval	0.25	Interval	0.3	Interval	0.05	Interval	0.1	Interval	0.05

Table 7
Selected pdf characteristics for container vessels.

Container Ships									
V_i/V_s		θ_t		l/L		w/B		d/D	
Normal		3-P Gamma		2-P Weibull		2-P Gamma		Lognormal	
N(0.6414,0.2324)		Γ(0.3845,0.3414,0.02625)		W(0.8836,0.8363)		Γ(1.568,0.06549)		lnN(-2.548,0.7144)	
Max	1	Max	0.36728	Max	0.5	Max	1	Max	0.5
Min	0.016216	Min	−0.04867	Min	0	Min	0	Min	0
Interval	0.175	Interval	0.05250	Interval	0.05	Interval	0.1	Interval	0.05

shall be dealt with as random variables. The limited number of available damage data for passenger ships has concluded to that all damage data, regardless of ship type and time period, shall be considered. The same analyses were undertaken by (HARDER, 1999–2003) and (GOALDS, 2009–2012).

5. Probability density distributions of random variables

The ship types involved in the collected database are regrouped into six categories, each encompasses several more specific types, as follows:

- All types: including all types of vessels in the database.

Table 8
Selected pdf characteristics for passenger vessels.

Passenger Ships									
V_i/V_s		θ_t		l/L		w/B		d/D	
Normal		2-P Weibull		logistic		Normal		Normal	
N(0.5489,0.2854)		W(1.13,0.365)		L(0.1412,0.07504)		N(0.1747,0.1112)		N(0.1333,0.08523)	
Max	1	max	1.16036	max	0.5	Max	1	max	0.5
Min	0.08823	min	0	min	0	Min	0	min	0
Interval	0.1	Interval	0.19	Interval	0.05	Interval	0.1	Interval	0.05
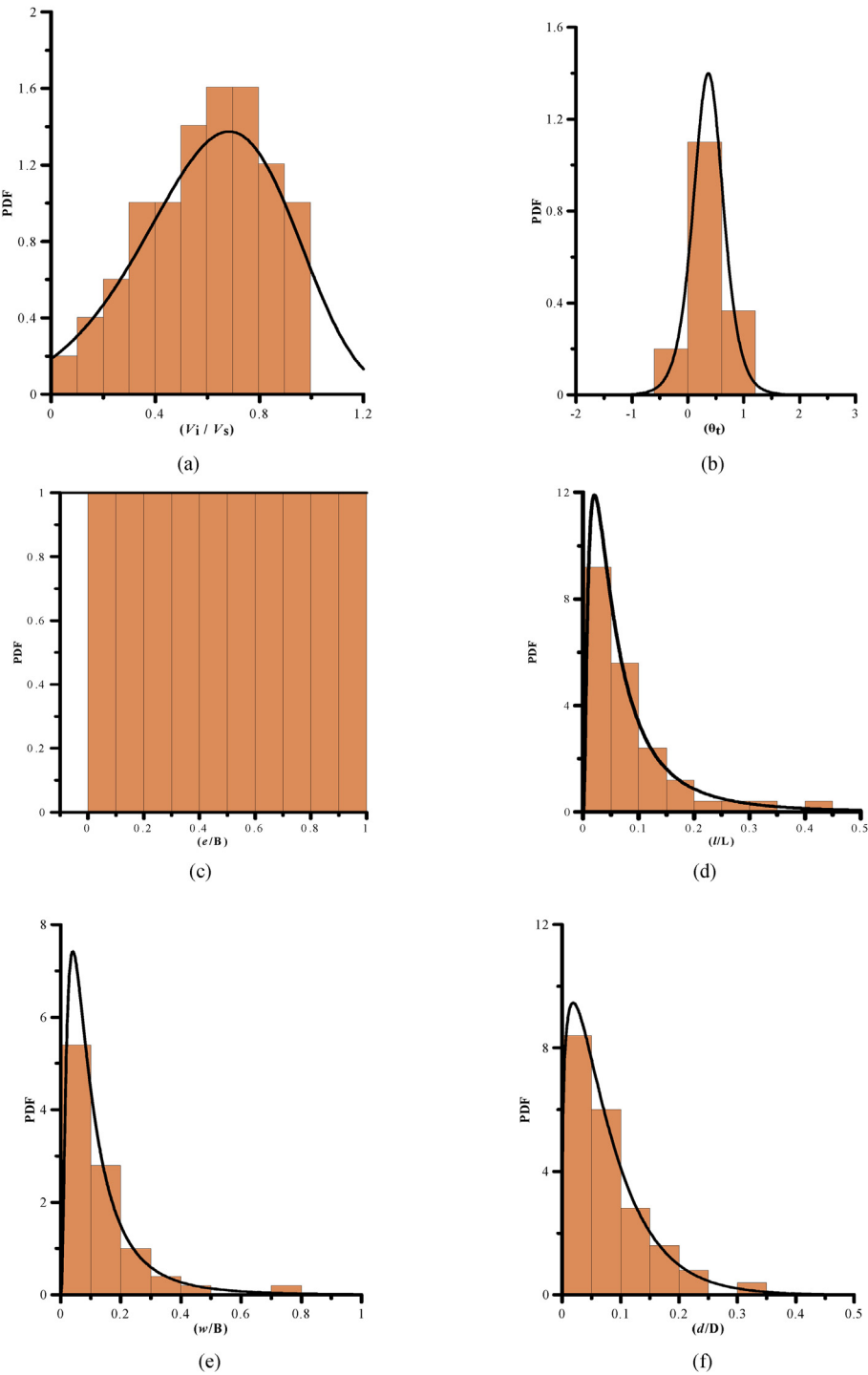
Fig. 15. Histograms fitted with pdfs for each grounding parameter of the selected 50 scenarios. (a) Non-dimensional impact speed (V_i/V_s); (b) Trim angle (θ_t); (c) Non-dimensional obstruction tip eccentricity (e/B); (d) Non-dimensional obstruction length (l/L); (e) Non-dimensional obstruction width (w/B); (f) Non-dimensional obstruction elevation (d/D).

Table 9
Fifty grounding scenarios selected for all type of ship categories as an illustrative example.

	V_i/V_s	θ_t	e/B	l/L	w/B	d/D
1	0.4533	0.2560	0.17	0.0334	0.1206	0.013953
2	0.9400	0.6498	0.83	0.1273	0.1151	0.098368
3	0.5875	0.7061	0.19	0.3080	0.1840	0.142854
4	0.3321	0.4024	0.47	0.2550	0.0329	0.214667
5	0.7671	0.3451	0.39	0.1957	0.0493	0.176504
6	0.7411	0.1889	0.71	0.0163	0.4784	0.085338
7	0.6904	0.4617	0.41	0.0414	0.0208	7.30E-03
8	0.4863	0.1704	0.49	0.0458	0.0411	0.134517
9	0.0457	0.2716	0.61	0.0280	0.0960	0.045137
10	0.3980	0.3016	0.91	0.0316	0.1265	1.63E-01
11	0.6397	−6.8E-03	0.97	0.0393	0.0578	0.09377
12	0.7804	0.8286	0.11	0.1608	0.1396	9.59E-03
13	0.9013	0.3738	0.37	0.0586	0.1733	0.022435
14	0.7283	0.5265	0.07	0.0506	0.2257	0.103271
15	0.5171	−0.1593	0.03	0.0793	0.0608	0.07774
16	0.5019	0.0568	0.89	0.0715	0.0840	0.02889
17	0.6778	0.2067	0.43	0.4086	0.1961	0.055653
18	0.5462	0.2867	0.63	0.0933	0.0438	0.0182
19	0.5740	0.4772	0.51	0.0180	0.0878	2.07E-03
20	0.8078	0.1076	0.69	0.0558	0.0113	0.031092
21	0.7541	0.7400	0.59	0.1048	0.0466	0.016083
22	0.6139	0.4169	0.67	0.0145	0.0357	0.061398
23	0.7156	0.6032	0.05	0.0127	0.0768	0.024567
24	0.3065	0.5442	0.85	0.0196	0.1099	0.058479
25	0.8674	0.6256	0.87	0.1479	0.0918	0.033325
26	0.6008	−0.0954	0.25	0.0836	0.0169	0.064419
27	0.8220	0.8925	0.93	0.0680	0.3337	0.011796
28	0.8517	0.4931	0.31	0.0107	0.2673	0.081446
29	0.1162	0.4465	0.75	0.2206	0.2098	0.052913
30	0.3775	0.3163	0.65	0.1115	0.1636	3.17E-01
31	0.3556	0.1300	0.99	0.0052	0.0273	0.114189
32	0.2469	−0.2542	0.35	0.0435	0.2446	0.108525
33	0.6651	0.5824	0.33	0.1189	0.0803	0.089437
34	0.5318	−0.4541	0.09	0.0298	0.0734	0.050251
35	0.9867	0.5628	0.23	0.1764	0.0638	0.037908
36	0.6269	−0.0467	0.13	0.0882	0.0242	0.047661
37	0.6525	0.1508	0.15	0.0353	0.3878	0.127072
38	0.4701	0.9874	0.27	0.0647	0.0669	0.040265
39	0.9621	0.5095	0.79	0.0246	0.2959	4.86E-03
40	0.2784	0.6764	0.95	0.0753	0.0521	0.152337
41	0.7030	0.0834	0.55	0.0481	0.1549	0.120339
42	0.5602	0.3594	0.77	0.0615	0.1004	0.247487
43	0.8839	0.2401	0.21	0.0263	0.1051	0.070808
44	0.8366	0.3880	0.45	0.1368	0.1328	0.035596
45	0.1686	0.0271	0.01	0.0085	0.0549	0.020314
46	0.9199	0.2237	0.53	0.0373	0.7109	1.93E-01
47	0.4174	0.7798	0.57	0.0531	0.0302	0.026717
48	0.4357	0.4316	0.73	0.0230	0.0384	0.042673
49	0.2110	0.3307	0.81	0.0988	0.1469	0.067552
50	0.7940	1.1873	0.29	0.0213	0.0701	0.074199

- Tankers: including crude, product and chemical tankers as well as gas carriers.
- Bulk carriers: including dry bulkers and coal carriers.
- Cargo vessels: including general cargo and refrigerated vessels.
- Container vessels.
- Passengers: including passenger vessels, ferries and Roll-on/roll-off (Ro-Ro) vessels.

5.1. All types of ships

The range and the variability of each parameter are investigated and illustrated in histograms that represent the historical data. The Goodness-of-Fit (GoF) tests are applied to formulate the probability density distribution using the Kolmogorov-Smirnov test (K-S) (Chakravarty et al., 1967). The K-S test assesses the statistic value which is the largest absolute value of the difference between the historical data and the candidate pdfs. Although there are many theoretical pdfs to fit the historical data, it is not practical to consider them all. Thus, only seven of the most commonly used pdfs are picked to designate the best to fit the

historical data. The better the distribution fits the historical data, the smaller the statistic value. Table 2 shows the test statistic value for the candidate pdfs for each parameter in the 'All types of vessels' category. As discussed in the earlier section, a uniform pdf is suggested to represent the data distribution of obstruction tip eccentricity (e) as a non-dimensional distance from the ship centerline to port or starboard side (-B/2, B/2).

To manage the effect of the histogram bin width (interval) on the distribution parameters, the so-called 'minimum COV criterion' is effectuated for the selected pdf for each parameter. In this step, the mean and COV values are examined for various histograms' bin width. The bin width that corresponds to the largest mean and the lowest COV is selected as shown in Fig. 13. The selected pdfs for each grounding parameter that best represent the historical data based on the examination results of the K-S test, and the effect of the histogram bin width are shown in Fig. 14.

5.2. Individual ship categories

The above steps are then applied to the other ship categories in the database until configuring the selected pdfs for each grounding scenario parameter is attained. The characteristics of the selected pdfs for tankers, bulk carriers, cargo vessels, container vessels and passenger vessels are recorded in Tables 4–8, respectively.

6. Probabilistic selection of grounding scenarios

The probability density functions determined in Section 5 are employed in a sampling process to stochastically select a limited number of grounding scenarios. In this study, the Latin hypercube sampling method (LHS) is used by implementing the selected pdfs to generate random values for each scenario parameters, with respect to the data range and variability. A Latin square is a square grid containing sample positions, if (and only if) there is only one sample in each row and each column. A Latin hypercube is the generalisation of this concept to an arbitrary number of dimensions, whereby each sample is the only one in each axis-aligned hyperplane containing it. By employing LHS, a total of 50 grounding scenarios are generated for 'All type of ships categories' as indicated in Table 3. Fig. 15 shows the histograms fitted with pdfs for each grounding parameter of the selected 50 scenarios shown in Table 9. To verify the selected scenarios resulted from the sampling, the comparisons shown in Fig. 16 illustrate historical data versus the selected 50 scenarios histograms fitted with the selected PDF for each grounding parameter.

7. Concluding remarks and further work

Grounding accidents are a threat at the maritime sector in terms of environmental and economic impacts, despite the cautionary measures devised recently as well as the developed navigational aids onboard. In overall, this paper aims at contributing to the decrease of the grounding consequences with an advanced technology to select a set of credible scenarios which are essential within the framework of quantitative grounding risk assessment and management.

First, a database was gathered, consisting of information of grounding accidents that happened over the course of 46 years, from various sources. Then, this data was revised and filtered to delete doubles and check missing data that might have been glossed over in the accident reports. The accidents in the database were then analyzed to divide the vessel into categories based on their type and to understand the main parameters that can be used to define and adequately describe a grounding incident. A goodness of fit (GoF) test was carried next to choose the most suitable probability density function (pdf) that would best represent the distribution of the data of each of these parameters for every type of vessel. After that, the data was distributed as a histogram with optimum bin width for a better representation to the chosen pdf.
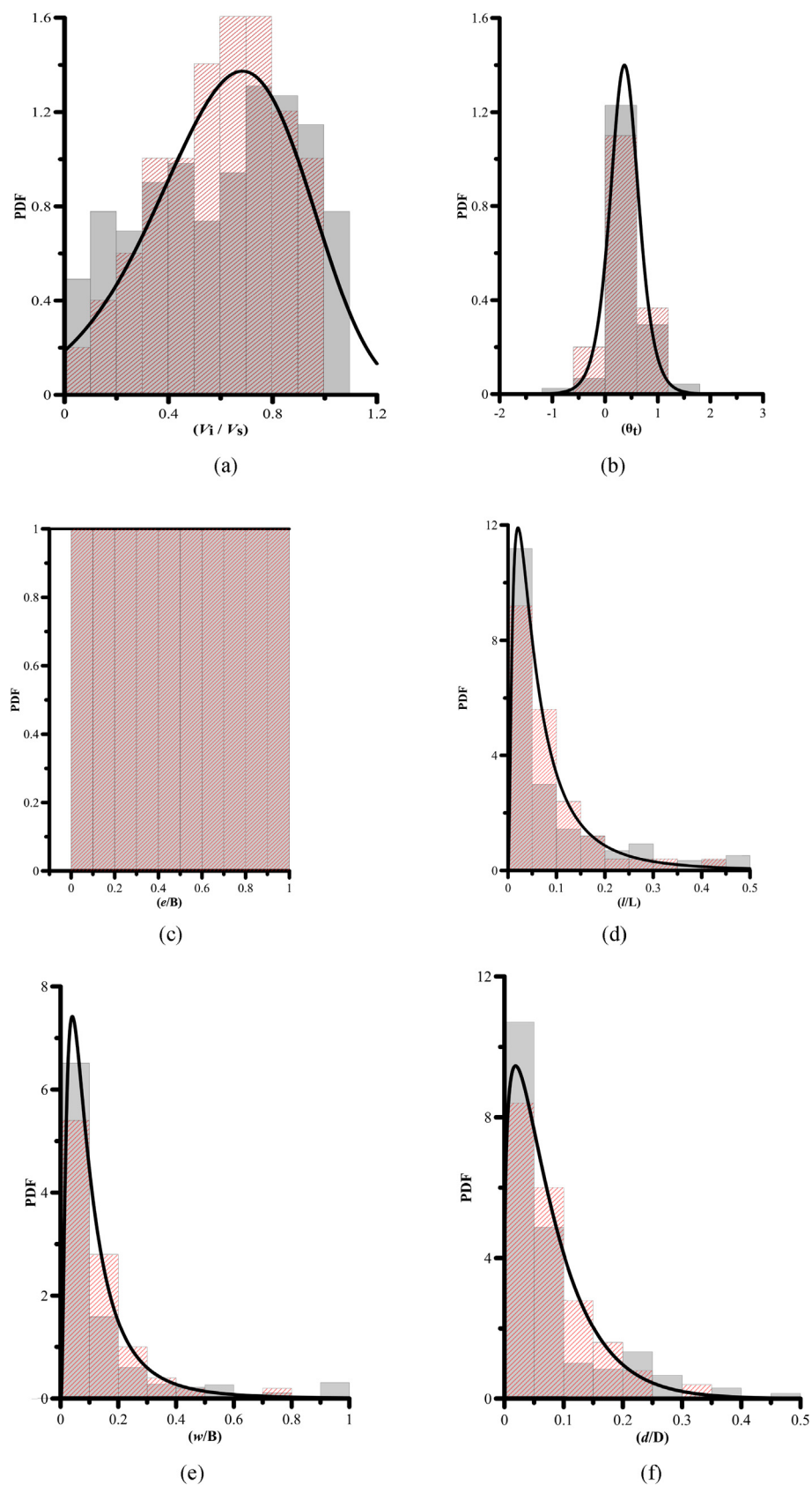
Fig. 16. Comparison of the historical data versus the 50 scenarios histograms fitted with the selected PDF (a) Non-dimensional impact speed (V_i/V_s); (b) Trim angle (θ_t); (c) Non-dimensional obstruction tip eccentricity (e/B); (d) Non-dimensional obstruction length (l/L); (e) Non-dimensional obstruction width (w/B); (f) Non-dimensional obstruction elevation (d/D).

The resulted histograms' particulars and the best-fit pdfs' shape parameters were then tabulated for an easier representation of the results. As a demonstrated example, the LHS method was used to randomize limited number of scenarios for all type of ships category, containing six non-dimensional parameters.

It was noticed that newly built vessels were more prone to experience grounding. This is may be come due to crew's inability and unfamiliarity to handle new technology equipment with the new ship. It also be noticed that the cargo vessels face more groundings compared to other types due to the nature of their shipping routes that mostly are short seas and trafficked coastal areas. On the other hand, old vessels (i.e., over 25 years) facing grounding with about 24.5% of the accidental database. This is because of several factors such as; degradations in the ship performance and the reliability of the mechanical, less advanced navigational equipment onboard as well as the improper bridge design. Concerning the ship speed at the moment of grounding, it was noted that the recorded speed lies between 80 and 100% of the ship's service speed due to a poor vessel's navigator awareness of the accident as well as no corrective actions prior the grounding event in some cases. The tabulated grounding parameters' pdf for diffirent type of vessels can be used to formulate a certain number of random scenarios to numerically simulate a reliable groundings with less uncertainty of the resulted damage. This in turn will be useful for grounding risk assessment.

Further works are now ongoing in terms of the analyses of frequency and consequences in association with selected grounding scenarios within the framework of quantitative grounding risk assessment.

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